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Characterization of the time dynamics of monthly satellite snow cover data on Mountain Chains in Lebanon

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SUMMARY

In this study, the time dynamics of the monthly means of the snow cover have been on Lebanese Mountain Chains from 2000 to 2012, derived from the MODIS Aqua/Terra satellite snow products was analyzed. This represents the longest satellite-based snow cover time series produced for Lebanon so far. Field survey was also carried out over the last three years in order to measure the in-situ snow/water equivalent and depth in different localities. Analyzing the regime of the snow cover in Mount-Lebanon (Western Mountain Chains) region, it was found that: (i) snowmelt accounts for about 31% of the rivers and springs discharge in Lebanon; (ii) consecutive peaks in the snow cover time series, representing the change-point between accumulation phase and ablation phase are present in three different patterns (edged, non-edged and double peaked); (iii) the areal snow coverage has big diversity between different years; (iv) the annual periodicity represents the most statistically significant and predominant frequency of the series contributing for about the 40% of the total variance of the snow cover series; (v) the long-term trend, totally hidden by the more powerful yearly component and detected by using the singular spectrum analysis (SSA), accounts for about the 33% of the total variance of the series; (vi) the long-term trend shows an apparent cyclic behavior with an estimated period (interval between the two minima) of about nine years; (vii) the comparison of the long-term trend with the North Atlantic Oscillation (NAO) monthly index reveals that the minima in 2009–2010 of the SSA long-term component coincides with a persistent negative phase in the NAO Index.

1. Introduction

Under climate change, mountain water resources represent an important issue (Jonas et al., 2009). In mountainous catchments snow contributes to a significant part of the total runoff (Barnett et al., 2005; Hock et al., 2006). As a consequence, investigating the space–time distribution of snow is crucial for monitoring mountain water resources and predicting future runoff. Among the several physical quantities characterizing snow, snow cover is important for several reasons, like in procedures of assimilation into hydrological and land-surface models to address the impact of snow on the accuracy of streamflow simulations (Clark et al., 2005), or in hydrological applications for the estimation of the snow/water equivalent (Jonas et al., 2009), with a direct influence, for instance, on the magnitude and timing of the spring freshet (Anderton et al., 2004; Garen and Marks, 2005).

The Lebanese mountains chains play a fundamental role in governing the distribution of rainfall and snow and possibly controlling the hydrologic response of most river systems (Mhawej et al., 2014). The distinguished geomorphologic setting of Lebanon on the Eastern Mediterranean basin is characterized by a unique topography, where two parallel Mountain Chains (Mount Lebanon and Anti-Lebanon) extend parallel to the shoreline, and are, then, separated by a land depression (Bekaa depression). Even though Lebanon encompasses a small area (i.e. 10452 km^2), it has a definite morphology, which makes it remarkable from the surrounding regions. Therefore, the extending Mountain Chains that face the Mediterranean constitute a meteorological barrier that receives cold air masses from the west, which are then condensed before they precipitate as rainfall and snow (Shaban and Darwich, 2013). This physiographic setting of Lebanon results an average precipitation rate of about 950 mm/yr, and exceeding 1500 mm/

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yr on mountain crests above 2500 m altitude, with an estimated annual snowpack volume between 1200 and 2000 MCM/yr, which is about 30–40% of the annual precipitation (Shaban et al., 2004; Aouad Rizk et al., 2005).

It is believed that water resources in Lebanon are abundant, since Lebanon hosts 15 issuing rivers and more than 2000 major springs; furthermore, snow covers annually more than 25% of Lebanon's territory. Groundwater potential reservoirs and karstic conduits are also dominant. Therefore, Lebanon is considered a country with sufficient water resources, whose water availability is estimated at 1350 m^3/capita/yr, against a water demand of about 220 m^3/capita/yr (El-Fadel et al., 2000; Shaban, 2011).

Recently, Lebanon has been facing an important issue in water resource management (El-Fadel et al., 2000; Fawaz, 2009; Shaban et al., 2014). Due to the changing climatic conditions and the growth of population, the water availability per capita decreased of 40–50% along with an increase in water demand. In addition, water resources in Lebanon have been deteriorated quantitatively and qualitatively due to the absence of legal controls and awareness of consumers. Therefore, it was demonstrated that the volume of water in some rivers and springs in Lebanon has remarkably decreased up to about 60% over the last few decades (Hamze et al., 2010; Shaban, 2011; Darwich et al., 2013); nevertheless, the increased population is still believed to be the most effective in this regard. Moreover, groundwater level has been drawdown by tens of meters in the major aquifers. Drought frequency increased in the eastern Mediterranean area over the 20th century (Hoerling et al., 2012) and may continue to increase in the 21th century (Smiatek et al., 2011). Climate projections in the region further indicate that the future runoff may decrease by 15% by the end of the 21th century (Smiatek et al., 2011).

Thus in order to establish the causes of the shortage, all water resources need to be investigated. The main component of these resources is snowmelt, which is the principal feeding source of rivers and springs. It is well stated that without snow, Lebanon would be a country without rivers and with few springs. Therefore, melting water from snow is still the last component to be reserved in Lebanon. Even though calculations of water volume derived from snow are still inadequate, the preliminary estimations evidenced its dominant role as a feeding-water source. Abd El-Al (1953) estimated that more than 60% of Ibrahim River water derived from snowmelt. Shaban et al. (2004) estimated that 1100 million m^3 of water results from snowmelt on Mount Lebanon (i.e. only the western Mountain Chains of Lebanon). This is equivalent to about 49% of water resources in the studied region. Shaban and Darwich (2013) calculated more than 2750 million m^3 as annual water volume melted from snow over the entire Lebanon (about 58% of the Lebanese water resources). All these results show the essential role of snow in replenishing water sources in Lebanon.

In past years, there were very few studies tackling snow cover in Lebanon. Some few field campaigns were conducted to measure snowpack depth Recently, the development of remote sensing techniques provided valuable means to perform reliable investigations on snow cover. In Lebanon, previous attempts focused on the application of satellite radar imaging to the estimation of the snow water equivalent (Bernier et al., 2003; Corbane et al., 2005). The accuracy of the retrievals was strongly limited by the heterogeneity of the Lebanese snow cover. Radar images were only available for a few dates. In contrast, low to mid-resolution optical remote sensing allows observing snow cover even on daily basis, as well as to estimate the geographic distribution of snow in Lebanon (Shaban et al., 2004; Bernier et al., 2003). Nevertheless, these recent obtained studies followed different approaches of remotely sensed data analysis, but measuring snow cover area and its physical controls and snow/water equivalent remain the major objectives.

In this study, a monthly time series of snow cover area on Lebanese Mountains since 2000 until 2012 derived from MODIS remote sensing data is presented. This is the first long-term time series of snow cover in Lebanon that was produced so far, up to our knowledge. Additionally, we perform the snow cover data analysis using advanced statistical methods, namely the robust periodogram analysis and the singular spectrum analysis (SSA).

2. Data sources

Monitoring the snow cover extent is important to understand the local contribution of snow to rivers discharges. The freely accessible Moderate Resolution Imaging Spectroradiometer (MODIS) eight days snow cover products at 500 m spatial resolution provides a valuable input both for local and regional snow cover monitoring and further hydrological studies. In this study, the MODIS–Terra (MOD10A2) and MODIS–Aqua (MYD10A2) Snow Cover 8-Day L3 Global 500 m Grid data sets were processed. Whereas MOD10A1 is affected by cloud cover, this is minimized by the use of the 8-day composite products of MOD10A2 (Liang et al., 2008). These products have been successfully applied in many regions worldwide for the monitoring of the snow cover spatiotemporal variations (e.g., Wang and Xie, 2009; Paudel and Andersen, 2011); and (iii) sometimes, along with other types of satellite images, to benefit of different advantages in both image types (Zhou et al., 2013; Mhawej et al., 2014).

The dataset contains the maximum snow cover extent over an eight-day compositing period and a chronology of snow occurrence observations. The MODIS snow cover data are based on a snow mapping algorithm that employs mainly a Normalized Difference Snow Index (NDSI). A detailed description of the MODIS snow products is given by Hall et al. (2002). The MODIS snow cover products are derived from MODIS daily observations of the entire Earth's surface every 1 or 2 days (Fig. 1); the data are acquired in 36 spectral bands or groups of wavelengths: from 0.4 μm to 14.5 μm with spatial resolution of 250 m (bands 1–2), of 500 m (bands 3–7) and of 1000 m (bands 8–36).

The raw data since February 2000 until June 2012 were downloaded from the National Snow and Ice Data Center (NSIDC) website. The whole dataset was analyzed using Matlab.

A first assessment using high resolution satellite images (Landsat) was carried out to compare snow cover area with those obtained from MODIS images. The discrimination between snowpack and clouds was performed by using the combination between the two MODIS products (i.e. Terra and Aqua). Landsat snow cover extent was estimated using a threshold of 0.4 on the NDSI. Regarding the detection of snow cover, Landsat and MOD10 products are very similar (except the case of complete snow melting). As it be can observed in Figs. 1–3, the MODIS 8-day (500 m) image match the high resolution Landsat (30 m) image corresponding to the maximum snow extent, when the MODIS snow and cloud detection algorithms is applied to Landsat images. The reader can also refer to Mhawej et al. (2014) who have further validated MOD10A1 snow product in Lebanon using several Landsat images.

The initial 8-days snow cover syntheses from MOD and MYD10A2 from MODIS data provided the extent of snow cover observed over 8-days. Further processing was performed in order to improve the snow cover estimates. The data were projected over Lebanon in UTM 33 North, and the different classes are merged according to "no snow" and "snow and/or lake/ice". An algorithm was developed to fill the gaps in such MODIS datasets (Hall et al., 2010; Parajka and Blöschl, 2008). Such algorithm was applied in 3 steps: (1) firstly Aqua/Terra products were combined on the base of a prioritization approach (Xie et al. (2009)); (2) then the gaps were filled with data of adjacent time steps; (3) finally, a spatial